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RADIATIVELY DRIVEN HYPERSONIC WIND TUNNEL

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13. SUPPLEMENTARY NOTES
This technical memo summarizes the work effort and includes a bibliography of reports, presentations, and papers produced under the effort.

14. ABSTRACT
Work conduced from August 1, 1992 until November 30, 1996 under support from the Air Force Arnold Engineering Development Center (AEDC), followed by continuing support from the Air Force Research Laboratory through September 30, 1998, established the foundation for the development of a new concept which is expected to extend the range of practical hypersonic wind tunnel testing from approximately Mach 8 to Mach 12 and beyond.

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FINAL REPORT FOR AEDC

RADIATIVELY-DRIVEN HYPERSONIC WIND TUNNEL
Grant #F40600-92-K-0002

JULY 27, 1999

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Work conducted from August 1, 1992 until November 30, 1996 under support from the Air Force Arnold Engineering Development Center (AEDC), followed by continuing support from the Air Force Research Laboratory through Sept. 30, 1998, has established the foundation for the development of a new concept which is expected to extend the range of practical hypersonic wind tunnel testing from approximately Mach 8 to Mach 12 and beyond. This project, which under Arnold Air Force Base sponsorship was called "A New Concept for a Hypersonic Wind Tunnel," and under AFRL sponsorship was titled, "The Princeton Radiatively-Driven Hypersonic Wind Tunnel," has been a collaborative effort involving substantive participation from the National Institute for Standards and Technology (NIST), Lawrence Livermore National Laboratories (LLNL), Sandia National Laboratories (SNL), the High Energy Laser System Test Facility at White Sands (HELSTF), General Atomics Corporation (GA), CPI/Varian, Boeing, and several groups in Russia, including the Institute for Hydrodynamics in Novosibirsk, the Avogadro Center, and TSAGI. Final reports from those collaborative efforts are included in Appendix 1 in this document.

Figure 1 is a block diagram indicating the various components of the Hypersonic Wind Tunnel program. The funding from AEDC and from AFRL supported fundamental research and concept development tasks which are represented in the lower portion of Fig. 1. Early in the project it

became clear that the ultimate performance of the wind tunnel would be limited by the pressure attainable in the plenum section. Modeling of the tunnel performance required that the equation-of-state of air be extended beyond the range where experiments have been made and into the region of ultrahigh pressure on the order of 20,000 atm and beyond. That work was done through collaborations with NIST, as well as with groups in Russia. The practical limit of high pressure technology, including the identification of various design concepts for achieving ultrahigh pressure for significantly long (many seconds) run times, led to the participation of the Institute of Hydrodynamics in Russia and Lawrence Livermore National Laboratory to examine the possibility of using "conventional" hydraulically-driven pressure intensifying approaches, and to the participation of the Avogadro Center in Russia to explore unconventional approaches including explosively-driven concepts. In addition, some work was undertaken in collaboration with Lawrence Livermore and the Institute for Hydrodynamics to study the survivability of various nozzle materials.

In order for this wind tunnel concept to operate successfully, a major fraction of the energy must be coupled into the flow downstream of the throat in the supersonic regime. This coupling must be accomplished in a uniform and stable manner in order to avoid unacceptable fluctuations of flow properties at the hypersonic test location. Since the air is in high speed motion, the energy can only be added by radiative or particle beam processes. Three such processes were identified and researched in this project. These included: lasers, microwaves, and electron beams.

After exploring the projected availability of high power laser systems and various energy coupling mechanisms, it was determined that the most promising laser-based approach was to use the high power hydrogen-fluoride laser which would deposit its energy into the air through excitation of carbon dioxide molecules. Early work in the program addressed the spectral overlap of the hydrogen-fluoride laser with the carbon dioxide molecular absorption, particularly at the high temperatures and pressures encountered in the nozzle. This work included a series of experiments conducted at the NIST Laboratory in Gaithersburg, over temperature ranges from room temperature to 1,000 K, and pressure ranges from atmospheric pressure to 1,000 atm. Simultaneously, a new theoretical approach was developed to predict pressure narrowing and other effects which occur under these conditions. Also associated with the laser research was a collaboration with Sandia National Laboratories exploring the potential of developing nuclear-pumped lasers that might also be appropriate for this application. In addition, the collaboration with the HELSTF facility at the White Sands proving ground was established with the expectation of using their chemical laser systems for laser energy addition tests. The HELSTF laboratory undertook a modification of their 10 KW deuterium-fluoride laser system to convert it to hydrogen-fluoride for this application, however, that conversion was not completed during the requisite contract period.

In order to establish the viability of predictably and uniformly adding energy to a high speed flow using a laser system, an experiment was conducted at Wright Laboratory using the 10 KW carbon-dioxide laser system at their LHMEL facility. This radiation is in the vicinity of 10.6 microns, rather than the 2.7 microns associated with the hydrogen-fluoride laser, and is not absorbed by any naturally occurring molecules in air at low temperatures. The air flow was, therefore, seeded with sulfur-hexafluoride to allow energy deposition to occur. The results showed approximately 10% change in Mach number, which was temporally and spatially stable, as predicted, and validated the concept of controllable energy addition to supersonic air flows.

Microwave energy addition was explored through collaboration with General Atomics and with CPI Varian Associates, Boeing Corporation, and Livermore National Laboratories. Early in this work, the oxygen absorption at 60 GHz was identified as a candidate for energy addition. It

became clear, however, that this absorption is too weak to allow significant energy deposition into air with reasonable microwave fields. The possibility of increasing the conductivity of air using high energy electron beams has been considered, but has been temporarily set aside because of the high e-beam power required and the system complexity. Furthermore, the complexity of coupling the microwave fields into the high pressure air flow was identified to be a major technological challenge. In contrast to lasers, microwaves cannot be brought in from the low pressure test section region since microwave radiation causes breakdown in low pressure air. Various alternative schemes to bringing microwaves, including aerodynamic windows, in through the walls were proposed and explored in detail by General Atomics. An alternative approach of bringing the microwaves in through the plenum section is currently being examined under separate funding at Princeton University, but is probably not feasible given the constraints of the ultrahigh pressure plenum engineering. The absence of a promising mechanism for energy deposition and the difficulties of coupling high power microwave radiation into the nozzle have led us to set microwave radiation aside, for the time being, as a practical approach for energy addition.

The concept of using electron beams for energy addition was not initially explored in detail since it was feared that the electron beams would cause significant chemistry to occur in the air and lead to a degradation of the flow quality. Given the many advantages of electron beams, not the least of which is the potential availability of high power electron beam sources, this degradation of the flow quality may be a secondary factor. It is also important to recognize that the electron beam can be steered and focused into the nozzle using magnetic fields, a control factor which is not available in the case of lasers or microwaves. Under Air Force Research Laboratory support, the possibility of using electron beams for energy addition has been explored in depth, in close collaboration with Sandia National Laboratories. This has now led to a series of experiments that were conducted last summer at Sandia National Laboratories demonstrating that electron beams could be used as a driver for this wind tunnel concept.

The major emphasis of both the AEDC-sponsored and the AFRL-sponsored program has been to develop a computational model that is capable of predicting the performance of a practical scale radiatively-driven hypersonic wind tunnel. This modeling effort has two primary components. The first is a fully coupled, one-dimensional inviscid model that is used to predict ideal wind tunnel performance and to establish performance limitations associated with this wind tunnel concept. The second model is a fully coupled, time-dependent, two-dimensional CFD code that includes optical ray tracing and turbulent boundary layer. These codes have been used in an iterative manner to design both the laser and electron beam energy addition experiments. In the case of the electron beam experiments, the iteration has required separate computational steps at Sandia National Laboratories using their Monte-Carlo electron beam trajectory codes for energy deposition. The experiments are largely directed towards proof-of-principle and code validation with a particular emphasis on the stability and uniformity of the laser- or electron beam-driven flow field.

A very important area of concern has been the understanding of what happens near the wall both in the throat and through the nozzle section. The ray tracing models suggest that the boundary layer refracts the laser beam away from the wall and back into the core of the flow because of the index-of-refraction gradient associated with the high temperature and resulting low density near the wall. While this process may serve to keep direct laser heating of the wall to a minimum, the very high stagnation enthalpy of the flow itself is of great concern. Such issues as the boundary layer growth rate, the recovery temperature, and thermal transport have not yet been studied. During this contract period, however, a 3,000 atm blow-down facility was constructed and tested at Livermore National Laboratories as a test bed for boundary layer growth and heat transfer

studies. Preliminary blow-down experiments were conducted at Livermore in order to establish safety criteria and determine the performance of the flow initiation and timing mechanisms. That facility has now been transferred to Princeton University where experimental studies are expected to begin soon.

The major accomplishments of this program are summarized in Steering Committee presentations and in papers which have been published primarily in conjunction with AIAA Technical Meetings. Copies of viewfoils presented to the Steering Committee are included in this report as Appendix 2, and copies of papers are reproduced in Appendix 3. The major outcome of this work has been to establish the viability of the Radiatively-Driven Hypersonic Wind Tunnel Concept, and to develop the computational models which can be used to predict the performance of such a facility for practical applications.

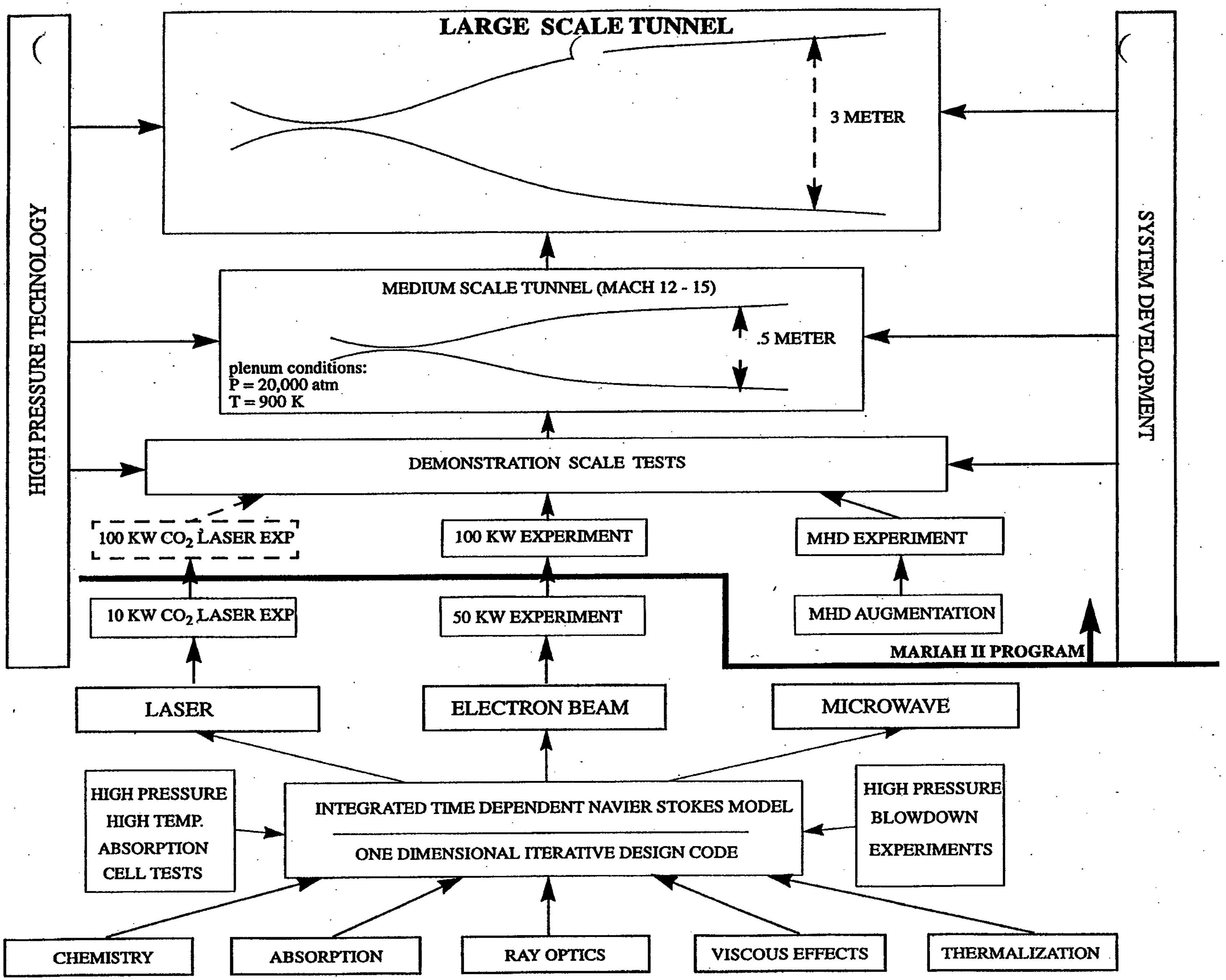

Figure 1: BLOCK DIAGRAM OF PROGRAM

RADIATIVELY DRIVEN HYPERSONIC WIND TUNNEL PROJECT
GRANT #F33615-96-C-3001
(150-6653)

APPENDICES TO FINAL REPORT (July 27, 1999)
PRINCETON UNIVERSITY
Princeton, NJ 08544

APPENDIX 1: PROJECT COHORT GROUP--REPORTS (Two Books)

BOOK 1 of 2:

Each cohort report is separated by a green sheet of paper. Blue sheets separate related reports by the same cohort group.

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APPENDIX 1: PROJECT COHORT GROUP--REPORTS (Two Books)

BOOK 2 of 2:

RUSSIAN ACADEMY OF SCIENCES, Avogadro Center, Moscow State University
Contract #F40600-95-C-0021 (Prof. G. Chernyi and S.A. Losev):

3/29/96	Report #1:	Ultrahigh Pressure Generation Using Explosive Compression
1/24/96	Report #2:	Thermodynamic Characterization and Transport Properties of Dense Air
2/14/96	Report #3:	Flow Chemistry of High Pressure Air
2/12/96	Report #4:	Energy Addition to Air Flow By Intensive Radiation
2/26/96	Report #5:	Numerical Simulation of Real Gas Flow with Local Heating and Thermochemical Nonequlibrium

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7/29/96		Radiatively Driven Wind Tunnel: State-of-the Art in Russian and Proposals for Future Research--Final Report *TSAGI (Central Aerohydrodynamic Institute), Russia* Dr. S. Chernyshev and M.N. Kogan
✓ July 1997		Conceptual Design for an Electron-Beam Heated Hypersonic Wind Tunnel *SANDIA NATIONAL LABORATORIES* *(Sandia Report #SAND97-1595)* Ronald J. Lipinski and Ronald P. Kensek
11/26/97		The Preliminary Study of the Ultimate Capabilities of the A-1 Type Facilities with Regard to Stagnation Pressures and Flow Rate/Time *RUSSIAN ACADEMY OF SCIENCES, LAVRENTYEV INSTITUTE OF HYDRODYNAMICS, Russia* M.E. Topchiyan et al.

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APPENDIX 2: STEERING COMMITTEE PRESENTATIONS (Three Books)

BOOK 1 of 3:

December 6-7, 1993	Summary of Princeton Hypersonic Tunnel Workshop ***PRINCETON UNIVERSITY, Princeton, NJ***
December 5, 1994	Hypersonic Wind Tunnel Meeting ***WRIGHT LABORATORIES, Dayton, OH***
February 1, 1995	Program Review--Hypersonic Wind Tunnel Project ***PRINCETON UNIVERSITY, Princeton, NJ***
April 5, 1995	Hypersonic Facility Research Project Review ***ARNOLD ENGINEERING DEVELOPMENT CENTER*** ***Tullahoma, TN***
June 15, 1995	Hypersonic Wind Tunnel Discussions ***WRIGHT-PATTERSON AIR FORCE BASE, Dayton, OH***
September 7, 1995	Hypersonic Wind Tunnel Discussions ***SANDIA NATIONAL LABORATORIES*** ***Albuquerque, NM***
November 30, 1995	Presentation to HELSTF ***U.S. ARMY SPACE & STRATEGIC DEFENSE COMMAND*** ***White Sands, NM***
✓December 7-8, 1995	Hypersonic Facility Research Review ***WRIGHT-PATTERSON AIR FORCE BASE*** ***Dayton, OH***

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APPENDIX 2: STEERING COMMITTEE PRESENTATIONS (Three Books)

BOOK 2 of 3:

March 5-6, 1996	Planning Meeting for the April 25-26, 1996 Technical Review--RDHWT *PRINCETON UNIVERSITY, Princeton, NJ*
April 8, 1996	Radiatively Driven Wind Tunnel *BOLLING AIR FORCE BASE, Washington, DC* *AIR FORCE OFFICE OF SCIENTIFIC RESEARCH*
✓April 25-26, 1996	Radiatively-Driven Hypersonic Wind Tunnel Concept--Program Review *WRIGHT-PATTERSON AIR FORCE BASE* *Dayton, OH*
May 29, 1996	Steering Committee Meeting--RDHWT *ARNOLD ENGINEERING DEVELOPMENT CENTER* Tullahoma, TN

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BOOK 3 of 3:

✓July 25-26, 1996	Steering Committee Meeting--RDHWT *NASA-LANGLEY, Hampton, VA*
✓December 11-12, 1996	Steering Committee Meeting--RDHWT *WRIGHT PATTERSON AIR FORCE BASE* *Dayton, OH*
✓April 23-24, 1997	Steering Committee Meeting--RDHWT *ARNOLD ENGINEERING DEVELOPMENT CENTER* *Tullahoma, TN*
/ April 8, 1998	Steering Committee Meeting - RDHWT *PRINCETON UNIVERSITY* *Princeton, NJ*
May 20, 1999	Steering Committee Meeting--RDHWT *SANDIA NATIONAL LABORATORIES* *Albuquerque, NM*

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APPENDIX 3: CONFERENCE/JOURNAL PAPERS (One Book)

BOOK 1 of 1:

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1. R. Miles, G. Brown, W. Lempert, D. Natelson, R. Yetter, J. Guest, G. Williams, and S. Bogdonoff, "RADIATIVELY DRIVEN HYPERSONIC WIND TUNNEL," Paper #AIAA-94-2472, 18th AIAA Aerospace Ground Testing Conference, Colorado Springs, CO, June 20-30, 1994.

2. S. Macheret, G. Williams, G. Comas, C. Meinrenken, W. Lempert, and R. Miles "ENERGY ADDITION AND THERMALIZATION ISSUES IN A RADIATIVELY-DRIVEN HYPERSONIC WIND TUNNEL," Paper #AIAA-95-2142, 30th AIAA Thermophysics Conference, San Diego, CA, June 19-22, 1995.

3. R.B. Miles, G.L. Brown, W.R. Lempert, R. Yetter, G.J. Williams, Jr., S.M. Bogdonoff, D. Natelson, and J.R. Guest, "RADIATIVELY-DRIVEN HYPERSONIC WIND TUNNEL," AIAA Journal, Vol. 33, No. 8, (August 1996), pp. 1463-1470.

4. G.L. Brown, A.P. Ratta, R.W. Anderson, L. Martinelli, W.R. Lempert, and R.B. Miles, "FLUID MECHANICS IN A RADIATIVELY-DRIVEN HYPERSONIC WIND TUNNEL--PREDICTION AND PRELIMINARY EXPERIMENT," Paper #AIAA-96-2199, 19th AIAA Advanced Measurement and Ground Testing Technology Conference, New Orleans, LA, June 17-20, 1996.

5. S. Macheret, C. Meinrenken, G. Williams, W. Gillespie, W. Lempert, and R. Miles, "RADIATIVE ENERGY ADDITION TO HIGH PRESSURE SUPERSONIC AIR," Paper AIAA-96-1984, 27th AIAA Fluid Dynamics Conference, New Orleans, LA, June 17-20, 1996.

6. C.J. Meinrenkin, W.D. Gillespie, S. Macheret, W.R. Lempert, and R.B. Miles, "TIME DOMAIN MODELING OF SPECTRAL COLLAPSE IN HIGH DENSITY MOLECULAR GASES," J. Chem. Phys. Vol. 106, No. 20, May 22, 1997, pp. 8299-8309.

7. S. O. Macheret, R.B. Miles, and G.L. Nelson, "FEASIBILITY STUDY OF A HYBRID MHD/RADIATIVELY-DRIVEN FACILITY FOR HYPERSONIC GROUND TESTING," Paper #AIAA-97-2429, 28th AIAA Plasmadynamics and Lasers Conference, Atlanta, GA, June 23-25, 1997.

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APPENDIX 3: CONFERENCE/JOURNAL PAPERS (One Book)

BOOK 1 of 1 (Continued):

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8. W.D. Gillespie, C.J. Meinrenken, W.R. Lempert, and R.B. Miles, "INTERBRANCH LINE-MIXING IN CO_2 (10^01) and (02^01) COMBINATION BANDS," J. Chem. Phys. Vol. 107, No. 15, October 22, 1997, pp. 5995-6002.

9. G.L. Brown, R.W. Anderson, A.E. Morgan, P.F. Barker, R.J. Lipinski, and R.B. Miles, "THE FLUID MECHANICS OF A RADIATIVELY-DRIVEN WIND TUNNEL: PREDICTIONS AND EXPERIMENT," Paper #AIAA-98-2747, AIAA 29th Plasmadynamics and Lasers Conference, Albuquerque, NM, June 15-18, 1998.

10. P.F. Barker, J.H. Grinstead, A.E. Morgan, P.J. Howard, G.L. Brown, and R.B. Miles, "OPTICAL DIAGNOSTICS FOR THE RADIATVELY-DRIVEN WIND TUNNEL," Paper #AIAA-98-2612, 20th AIAA Advanced Measurement and Ground Testing Technology Conference, Albuquerque, NM, June 15-18, 1998.

11. A.E. Morgan, P.F. Barker, R.W. Anderson, J.H. Grinstead, G.L. Brown, and R.B. Miles, "PRELIMINARY EXPERIMETNS IN THE DEVELOPMENT OF THE RADIATIVELY DRIVEN WIND TUNNEL," Paper #AIAA-98-2498, 20th AIAA Advanced Measurement and Ground Testing Technology Conference, Albuquerque, NM, June 15-18, 1998.

12. R.B. Miles and G.L. Brown, "ENERGY ADDITION MECHANISMS FOR RADIATIVELY-DRIVEN WIND TUNNEL: PREDICTIONS & EXPERIMENTS," Paper #AIAA-98-2748, AIAA 29th Plasmadynamics and Lasers Conference, Albuquerque, NM, June 15-18, 1998.

13. S.O. Macheret, M.N. Shneider, R.B. Miles, R.L. Lipinski, and G.L. Nelson, "MHD ACCELERATION OF SUPERSONIC AIR FLOWS USING ELECTRON BEAM-ENHANCED CONDUCTIVITY," Paper #AIAA-98-2922, AIAA 29th Plasmadynamics and Lasers Conference, Albuquerque, NM, June 15-18, 1998.

14. P.J. Erbland, R. Murray, M.R. Etz, M. Huntley, and R.B. Miles, "IMAGING THE EVOLUTION OF TURBULENT STRUCTURES IN A HYPERSONIC BOUNDARY LAYER," Paper #AIAA-99-0769, 37th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 11-14, 1999.

15. R.W. Anderson, G.L. Brown, and R.B. Miles, "PERFORMANCE CHARACTERIZATION OF A RADIATIVELY-DRIVEN HYPERSONIC WIND TUNNEL," Paper #AIAA-99-0822, 37th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 11-14, 1999.

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APPENDIX 3: CONFERENCE/JOURNAL PAPERS (One Book)

BOOK 1 of 1 (Continued):

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16. P. Barker, J. Grinstead, A. Morgan, R. Anderson, P. Howard, G. Brown, R. Miles, R. Lipinski, K. Reed, G. Pena, L. Schneider, "RADIATIVELY-DRIVEN WIND TUNNEL EXPERIMENT WITH A 30 kW ELECTRON BEAM," Paper #AIAA-99-0688, 37th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 11-14, 1999.

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